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# Water use efficiency among dry bean landraces and cultivars in drought-stressed and non-stressed environments

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**Abstract** The agricultural use of water is higher than 85% in the western USA, resulting in an increasing water deficit in the region; this situation is commonly encountered throughout the world where irrigated and irrigation-assisted production systems are operational. The objective of this study was to examine differences among dry bean (*Phaseolus vulgaris* L.) landraces and cultivars in terms of water use efficiency (WUE), subsequently identifying those with a high water use efficiency. Six medium-seeded (25–40 g 100 seed wt$^{-1}$) landraces and cultivars of pinto and red market classes were evaluated in intermittent drought-stressed (DS) and non-stressed (NS) environments at Kimberly, Idaho, USA in 2003 and 2004. Each market class comprised one each of a landrace and old and new cultivars. Mean evapotranspiration (ET) in the NS environment was 384 mm in 2003 and 432 mm in 2004; the respective ET values in the DS environment were 309 and 268 mm. Mean seed yield was higher in the DS (2678 kg ha$^{-1}$) and NS (3779 kg ha$^{-1}$) environments in 2004 than in 2003 (688 and 1800 kg ha$^{-1}$, respectively). Under severe drought stress in 2003, WUE in the pinto bean ranged from 1.5 for the Common Pinto landrace to 4.4 kg ha$^{-1}$ mm$^{-1}$ water for cv. Othello. The Common Red Mexican landrace had the highest WUE (3.7), followed by cvs. NW 63 (2.8) and UI 259 (1.4) in the red market class. Under favorable milder climatic conditions in 2004, the mean WUE value was 10 kg ha$^{-1}$ mm$^{-1}$ water in the DS environment and 8.7 kg ha$^{-1}$ mm$^{-1}$ water in the NS environment. We conclude that dry bean landraces and cultivars with high WUE should be used to reduce dependence on irrigation water and to develop drought-resistant cultivars to maximize yield and WUE.

**Keywords** Breeding · Drought resistance · Evapotranspiration · *Phaseolus vulgaris* L. · Seed yield

**Abbreviations**

| | |
|---|---|
| DS | Intermittent drought-stressed |
| DSI | Drought susceptibility index |
| ET | Evapotranspiration |
| NS | Non-stressed |
| PR | Percentage reduction in seed yield due to drought stress |
| WUE | Water use efficiency |

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## Introduction

Net water requirement for a 90- to 100-day dry bean crop ranges from 350 to 500 mm depending upon the soil, climate, and cultivar (Allen et al. 2000). Adequate soil moisture (i.e., near field capacity) is essential for good emergence and crop establishment. However, during the early vegetative growth stages water requirements for dry bean are relatively low such that farmers often do not irrigate for the first 3–4 weeks after planting in the western USA. The water requirement and the frequency of irrigation increase as the plant canopy develops and soil coverage or leaf area index increases. Accordingly, the adverse effects of water deficit or drought are enhanced such that the crop becomes increasingly more sensitive to drought during the pre-flowering and reproductive stages. The water requirement of dry bean sharply declines after pod and seed development. In addition, early-maturing short cultivars would be expected to have a relatively lower net water requirement than full-season, late-maturing tall cultivars. Plant traits associated with water requirement include transpiration rate, osmotic potential, stomatal conductance, and water retention capacity, while the most important meteorological factors affecting crop water requirement are air temperature and humidity, solar radiation, and wind speed (Allen et al. 1998). In hot dry arid regions such as those found in southern Idaho, dry bean and other crops use large quantities of water for optimum growth due to the profusion of energy and the desiccating influence of the atmosphere. Furthermore, vapor removal is affected by wind speed because air movement transfers water vapor above the surface in a manner that is positively correlated with evapotranspiration (ET, the sum of the water evaporated from soil surface and water transpired by plants).

Water use efficiency (WUE), which in the present study is the ratio of seed yield to water utilized, is generally inversely proportional to the severity of the drought stress; for example, mild (i.e., ≤25% reduction in seed yield due to drought stress; expressed as the drought intensity index, DDI ≤0.25) to high (i.e., DDI >0.50) drought stress reduces (20–100%) overall plant growth or biomass yield, number of seeds and pods, harvest index (the ratio of seed yield to biomass yield), seed yield, seed weight, and seed quality in dry bean (Frahm et al. 2004; Padilla-Ramírez et al. 2005; Ramirez-Vallejo and Kelly 1998; Terán and Singh 2002). Root growth and development (Sponchiado et al. 1989; White and Castillo 1992), nodulation and biological nitrogen fixation (Ramos et al. 1999; Serraj and Sinclair 1998), other microbial activities, and plant and seed uptake and utilization of nutrients (Guida dos Santos, 2004; Muñoz-Perea et al. 2005; North and Nobel 1997) are also adversely affected by drought stress. Moreover, root rot and *Beet curly top virus* (a leafhopper-vectored curtoviral disease) may aggravate drought stress in the western USA. In the tropics, dry bean crops subjected to drought stress may become prone to damage by leafhoppers (*Empoasca kraemeri* Ross and Moore).

From among the various biochemical, morphological, physiological, seed yield, and related traits, dry bean researchers have found seed yield measured across contrasting drought-stressed (DS) and non-stressed (NS) environments to be the most reliable integrated measure of drought resistance (Abebe and Brick 2003; Frahm et al. 2004; Ramirez-Vallejo and Kelly 1998; Terán and Singh 2002; White et al. 1994a). Narrow-sense heritability of seed yield has been found to vary between 0.09 ± 0.19 and 0.80 ± 0.15 depending upon the population used, the growing environment, and the level of drought stress (Ramirez-Vallejo and Kelly 1998; Singh 1995; White et al. 1994b). Large differences for drought resistance occur in dry bean. Among the various dry bean germplasms, the large-seeded (generally >40 g 100 seed $wt^{-1}$) Andean bean (e.g., dark and light red kidney, cranberry, and white kidney) is the most susceptible to drought, followed by the small-seeded (e.g., black and navy with <25 g 100 seed $wt^{-1}$) bean in the western USA (Singh et al. 2001). The highest levels of drought resistance are found in medium-seeded cultivars of the pink, red, pinto, and great northern market classes belonging to race Durango (Terán and Singh 2002). These Durango race (synonymous with Gene Pool 5; Singh 1989) cultivars were initially domesticated in the semi-arid central and northern Mexican highlands (Singh et al. 1991) and subsequently introduced into the western USA by Native Americans who have grown them under non-irrigated or dryland, unfertilized, and pesticide-free subsistence production systems for centuries. By 1939, 476,344 acres of dryland bean were grown mostly in Arizona, New Mexico, California, Colorado, and Idaho (Mimms and Zaumeyer 1947).

The objective of the present study was to determine WUE for each of two dry bean landraces and relatively old and new cultivars, hereafter collectively referred to as genotypes, unless otherwise specified, belonging to race Durango.

## Materials and methods

### Dry bean genotypes

Six of 16 genotypes (Muñoz-Perea 2005; Muñoz-Perea et al. 2005, 2006) of dry bean were used to estimate WUE in NS and DS environments at the University of Idaho, Kimberly Research and Extension Center, Idaho in 2003 and 2004. The genotypes were selected based on their seed yield in prior studies carried out between 1999 and 2001 in southern Idaho (Singh et al. 2001). These genotypes included each of two dry bean landraces (Common Pinto, Common Red Mexican) and relatively old (Othello, NW 63; released by Burke et al. 1995 and Burke 1982, respectively) and new (UI 259 and UI 320; released by Myers et al. 2001a, b, respectively) cultivars.

### Experimental design

Six dry bean genotypes were arranged in a randomized complete block design with four replicates each in NS and DS environments. However, for the WUE measurements only two of the four replicates were used. Each plot consisted of eight 7.62-m-long rows with an inter-row spacing of 0.56 m. An average of 23 seeds per linear meter were planted. The NS and DS plots were planted adjacent to each other in the same field separated by a band of eight rows of dry bean under drought stress to reduce the lateral movement of water from NS to DS plots.

### Water applications

The NS experiment consisted of seven irrigations in 2003 and five irrigations in 2004, including the pre-plant irrigation that met the full irrigation needs. The DS experiment received four irrigations in 2003 and two irrigations in 2004. The amount of water applied by irrigation in the DS and NS plots was monitored using three pairs of small trapezoidal flumes. Each pair of flumes was located in the same furrow, one flume at the top and the other at the bottom of the experimental field. Water flow rate passing through the flumes ($Q$) and water applied (WA) were determined using the equations: $Q = 13.92(\mathrm{h}^{-0.15})$ and $\mathrm{WA} = [(Q_\mathrm{h}-Q_\mathrm{b})/LW)]\mathrm{t}$, where $Q$ is the water flow in liters per hour that passed through each flume. The gauge units (h) were in centimeters. WA is the amount of water (mm) infiltrated into the soil. The $Q_\mathrm{h}$ and $Q_\mathrm{b}$ represent water flow through the furrow at the top and bottom of the field, respectively. The $L$ and $W$ are furrow length and furrow spacing width (m), respectively, and t is the number of hours of irrigation. In all treatments, alternate rows were irrigated, which is a normal practice in southern Idaho for dry and green bean. Therefore, $W = 2\ (0.56) = 1.12$ m.

### Measurement of water use, ET, and WUE

For the gravimetric measurement of soil water content in each plot, soil samples were taken after planting, 1 day before and 2 days after each irrigation, and 1 day before harvest. In 2003, the gravimetric water content was estimated by taking soil samples with an auger every 0.2 m until a depth of 2 m was reached, with the exception of the first 0.2 m where two samples were taken, representing 0–0.1 and 0.1–0.2 m. The 11 soil samples at each site were collected in standard metal cans and weighed before and after drying in an oven at 105°C for 24 h. In 2004, only the first and last samplings were taken down to 2 m; all other samplings were taken to a depth of 1.2 m because in 2003 changes in water content below

1.2 m were very small or nil. The water content on a dry mass basis ($\theta_m$) was calculated using the equation: $\theta_m = [(M_w - M_s)/(M_s - C)] \times 100\%$, where $M_w$ is the mass of wet soil (g) before drying, $M_s$ is the dry soil mass (g), and $C$ is the can mass (g). The equation $\theta_v = \rho_s\theta_m/\rho_w$ , where $\rho_s$ is the soil density and $\rho_w$ is water density, was used to determine the volumetric ($\theta_v$) water content (%). The soil density for each sample depth was determined by taking cylindrical soil samples with a ''Madera'' bulk density sampler (Precision Machine Shop, Lincoln, Neb.), and estimating it as the dry soil mass divided by the volume of the cylindrical soil sample ($V_c$ = diameter × length) as $\rho_s = M_s/V_c$. The volumetric water content was converted to equivalent depth units over the treatment units using the equation $W_c = 10 (\theta_v D)$, where $W_c$ is water content in millimeters, $D$ is the sample depth in meters, and $\theta_v$ is expressed as the ratio centimeters/meters. The ET for each genotype was determined for every period between irrigations using the equation: $ET = [(\theta_{va} - \theta_{vb}) + P/\Delta t]\ t + P$, where $\theta_{va}$ is the volumetric water content after irrigation and $\theta_{vb}$ is the volumetric water content before irrigation, $\Delta t$ is the number of days between samplings, $t$ is the total length of time in days between irrigations, and $P$ is precipitation during the period. Because the change in $\theta_v$ at depth >1 m was essentially zero, we assumed that all of the change in $\theta_v$ was due to ET and that no deep flux of water from the root zone occurred. The water table in this area is >50 m depth. The WUE = $Y$/ET values (kg ha$^{-1}$ mm$^{-1}$ water utilized) were determined for each dry bean genotype by dividing seed yield by ET.

The water use and the impacts of the DS treatment were also monitored through measurements of the water potential in kiloPascals (kPa) at depths of 0.23, 0.46, and 0.92 m. The monitoring system used Watermark soil water potential sensors (Irrometer Company, Riverside, Calif.) connected to AM400 dataloggers (Hansen Company, East Wenatchee, Wash.). The sensors were attached to 0.5-inch PVC tubes to facilitate their installation and recovery. The AM400 datalogger recorded water potential every 8 h. Data were downloaded to a computer before the loggers were removed at harvest. Thus, six AM400 dataloggers and 36 soil moisture sensors were used in NS and DS environments. Every datalogger recorded data at three depths for two genotypes. In addition, each datalogger recorded soil temperature at a depth of 0.31 m. The lack of significant response in soil water potential at 0.92 m in all treatments – even after wetting events – supported the assumption that very little water was extracted by roots at depths below 1 m and that little or no deep percolation occurred. Mean daily precipitation, minimum, maximum, and mean air temperature, solar radiation, ET calculated by the Kimberly-Penman equation (Wright 1982), mean humidity, and average wind speed were recorded at the Twin Falls Agrimet Station located at a latitude of 42°32′46″ and a longitude of 114°20′43″ at the USDA-ARS North West Irrigation Research Center near Kimberly (http://www.usbr.gov/gp/agrimet/index.cfm), which was <1000 m from the plot.

Biomass yield (kg ha$^{-1}$) was determined for each genotype by cutting ten plants at ground level at maturity and drying at 60°C for 3 days. The six central rows (25.60 m$^2$) were cut at 108 days after planting in 2003 and 100 days after planting in 2004, threshed 8 days later, cleaned, and dried, following which the seed yield was recorded (kg ha$^{-1}$) at 12% moisture by weight. The harvest index was determined as the ratio between seed and biomass yield. Weight (g) of 100 seeds taken randomly was recorded. The drought intensity index (DII) for each year and the drought susceptibility index (DSI) and percentage reduction (PR) due to drought stress were calculated for each genotype according to Fischer and Maurer (1978). All data were analyzed using the SAS (ver. 9.1.3) GLM procedure (SAS 2004). For additional details on materials and methods, the readers are referred to Muñoz-Perea (2005) and Muñoz-Perea et al. (2006).

## Results and discussion

Drought stress was more severe in 2003 (causing an average reduction in seed yield of 62%) than in 2004 (27% reduction) even though two additional irrigations were applied to both the NS and DS plots in 2003 and the precipitation was higher

**Table 1** Number of irrigations and amount of water applied to two dry bean landraces and four cultivars in non-stressed (NS) and intermittent drought-stressed (DS) environments and rainfall, humidity, temperature, and solar radiation between May 28 and September 13 at Kimberly, Idaho in 2003 and 2004

| Climatic variable | 2003 | | 2004 | |
|---|---|---|---|---|
| | NS | DS | NS | DS |
| Number of irrigations | 7 | 4 | 5 | 2 |
| Water applied (mm) | 661 | 378 | 571 | 201 |
| Rainfall (mm) | 63 | | 36 | |
| Number of days humidity <45% | 52 | | 33 | |
| Number of days evapotranspiration >8 mm day$^{-1}$ | 62 | | 47 | |
| Number of days maximum temperature >35°C | 18 | | 2 | |
| Number of days solar radiation >29.3 MJ m$^{-2}$ day$^{-1}$ | 44 | | 23 | |

in that year (Table 1). The severity of DS in 2003 was due to larger evaporative demand that year. For example, there were more days with a maximum temperature above 35°C in 2003 (18 days) than in 2004 (2 days). Similarly, days with a solar radiation above 29.3 MJ m$^{-2}$ day$^{-1}$ were more frequent in 2003 (44 days) than in 2004 (23 days). Consequently, ET values above 8 mm day$^{-1}$ occurred at a higher frequency in 2003 (62 days) than in 2004 (47 days). Mean air temperature for the normal growth and development of cultivars of race Durango is 22°C (Singh 1989). Daily mean air temperatures above 28°C cause excessive flower drop, a reduction in pollen viability, and the abortion of fertilized ovules (Masaya and White 1991). The number of days with a mean air temperature exceeding 25°C (11) and with a daily maximum temperature above 35°C (18 days) during flowering and seed-filling periods in 2003 accentuated the drought stress and even reduced biomass and seed yield for the NS treatments. Furthermore, in dry bean, maximum photosynthesis occurs when solar radiation is between 25 and 27 MJ m$^{-2}$ day$^{-1}$ (White and Izquierdo 1991).

The six dry bean genotypes studied here mostly used water available above a soil depth of 1 m even in the more severe DS environment in 2003 (Fig. 1). Although roots of some dry bean genotypes may reach depths >1.2 m (Allen et al. 2000; Sponchiado et al. 1989), intermittent drought, especially early in the crop development, very likely reduced overall root growth; consequently, the differences in water potential among the six genotypes at soil depths of 0.92 m were non-significant ($P < 0.03$). These results are similar to those reported by Al-Kaisi et al. (1999) in southwestern Colorado, which indicated that dry bean extracted water down to a depth of 0.6 m under DS conditions and only down to 0.3 m under NS conditions. Median root length of 0.5 m and a maximum root length of 1 m were observed for dry bean using a minirhizotron in the dryland of North Dakota (Merrill et al. 2002). In addition, root density was greater between soil depths of 0.3 and 0.5 m.

Among the pinto market class of dry bean, Othello tended to have slightly higher ET in the NS environment in 2003 and in both environments in 2004 (Table 2). However, the most striking differences were observed under more severe drought conditions of 2003 in which Othello had a significantly lower ET in DS than Common Pinto and UI 320, probably because the former reduced its total transpiration by having a more compact plant canopy. In addition, ET may be biased in situations where plants do not cover enough soil surface and the soil evaporation accounts for the major water loss (Jones 2004). Because all three pinto genotypes were relatively early maturing and possessed a similar growth habit, any differences in their canopy cover would have been small. The greater reduction in ET by Othello under the DS treatment in 2003 may be due to its root characteristics. With the exception of the DS environment in 2004, there were significant ($P > 0.03$) differences in ET values among the three dry bean genotypes of the red market class. Common Red Mexican had a slightly higher ET in the NS environment in both years, whereas UI 259 had higher values in the DS environment.

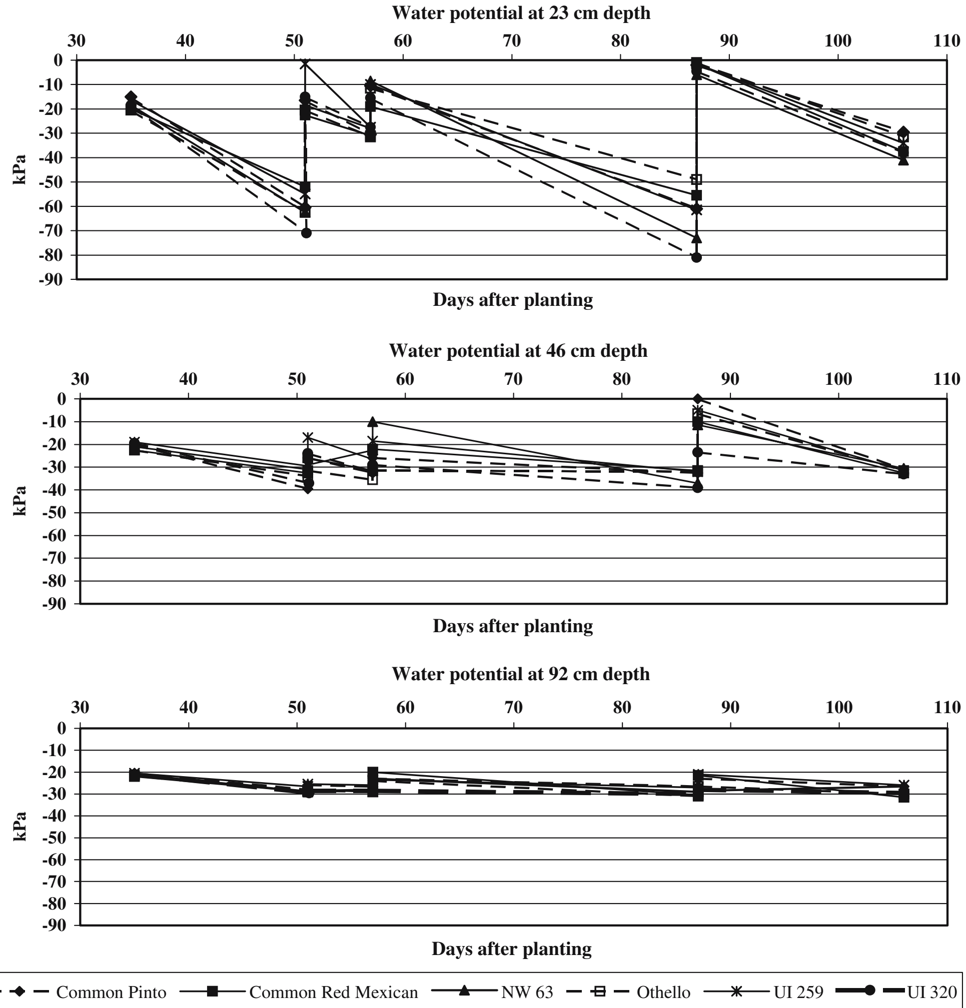


**Fig. 1** Water potential at soil depths of 23, 46, and 92 cm before and after each of four irrigations for two dry bean landraces and four cultivars evaluated under an intermittently drought-stressed environment at Kimberly, Idaho in 2003. The second, fifth, and sixth irrigation were skipped. *High peaks* represent water potential measurements after irrigation; *low peaks*, before irrigation.

There were significant differences for biomass and seed yield and harvest index between 2003 and 2004 in both the NS and DS environments (Table 2). In general, the values for these three traits for all genotypes in the NS and DS environments were lower in 2003 than in 2004. In both years in both environments, the mean seed yield of cultivars of the red market class was slightly higher than that of cultivars of the pinto market class. Common Pinto and UI 320 had a lower seed yield than Othello in the NS and DS environments in 2003 and in DS in 2004. Among the red genotypes, Common Red Mexican had the highest seed yield in the NS and DS environments in 2003, but the differences between the three genotypes were not significant in either environment in 2004.

Drought stress in 2003 resulted in a marked reduction in biomass and seed yield and harvest index (Table 2). For example, seed yield reduction ranged from 34% for Othello to 76% for Common Pinto. A much smaller reduction occurred in 2004 due to a milder drought stress (Table 1). Othello and Common Red Mexican had DSI values of less than 1.0 in both years; in contrast, Common Pinto and UI 320, also early

**Table 2** Mean biomass yield, seed yield, harvest index, evapotranspiration, water use efficiency, percentage reduction in seed yield due to drought stress, and drought susceptibility index for two dry bean landraces and four cultivars evaluated in NS and DS environments at Kimberly, Idaho in 2003 and 2004

| Genotype | 2003 | | | | | | | | | | | | 2004 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NS | | | | | DS | | | | | PR | DSI | NS | | | | | DS | | | | | PR | DSI |
| | BY[a] | SY | HI | ET | WUE | BY | SY | HI | ET | WUE | | | BY[a] | SY | HI | ET | WUE | BY | SY | HI | ET | WUE | | |
| Pinto | | | | | | | | | | | | | | | | | | | | | | | | |
| Common Pinto | 4638 | 1520 | 0.34 | 380 | 4.0 | 2201 | 359 | 0.14 | 338 | 1.1 | 76 | 1.2 | 8161 | 3312 | 0.41 | 378 | 8.8 | 6328 | 1996 | 0.33 | 248 | 8.0 | 40 | 1.5 |
| Othello | 5437 | 1805 | 0.34 | 457 | 3.9 | 4103 | 1199 | 0.28 | 270 | 4.4 | 34 | 0.5 | 7123 | 3611 | 0.52 | 422 | 8.6 | 6412 | 2762 | 0.44 | 269 | 10.3 | 24 | 0.9 |
| UI 320 | 4473 | 1407 | 0.32 | 414 | 3.4 | 2400 | 502 | 0.19 | 308 | 1.6 | 64 | 1.0 | 9709 | 3645 | 0.40 | 408 | 8.9 | 7173 | 2415 | 0.36 | 239 | 10.1 | 34 | 1.2 |
| Red | | | | | | | | | | | | | | | | | | | | | | | | |
| Common Red Mexican | 6668 | 2162 | 0.33 | 393 | 5.4 | 4401 | 1164 | 0.26 | 312 | 3.7 | 46 | 0.7 | 9078 | 3671 | 0.41 | 548 | 6.7 | 7263 | 2836 | 0.42 | 274 | 10.3 | 23 | 0.8 |
| NW 63 | 5737 | 2008 | 0.35 | 318 | 6.3 | 3277 | 824 | 0.25 | 292 | 2.8 | 59 | 1.0 | 9389 | 3951 | 0.43 | 463 | 8.5 | 7140 | 2943 | 0.42 | 282 | 10.4 | 26 | 0.9 |
| UI 259 | 5697 | 1850 | 0.33 | 343 | 5.4 | 3167 | 471 | 0.13 | 334 | 1.4 | 75 | 1.2 | 8479 | 4031 | 0.49 | 369 | 10.9 | 6104 | 2928 | 0.48 | 297 | 9.9 | 27 | 1.0 |
| Mean | 5442 | 1792 | 0.33 | 384 | 4.7 | 3258 | 753 | 0.21 | 309 | 2.5 | 59 | 0.9 | 8657 | 3704 | 0.44 | 431 | 8.7 | 6737 | 2646 | 0.41 | 268 | 9.8 | 29 | 1.1 |
| LSD[b] (0.05) | 1084 | 204 | 0.07 | 63 | 1.7 | 1596 | 630 | 0.15 | 33 | 2.0 | | | 682 | 422 | 0.11 | 84 | 2.0 | 2325 | 385 | 0.13 | 27 | 1.3 | | |

[a] BY, Mean biomass ( kg $ha^{-1}$); SY, seed yield (kg $ha^{-1}$); HI, harvest index; ET, evapotranspiration ( mm water); WUE, seed yield (kg $ha^{-1}$ $mm^{-1}$ water); PR, percentage reduction in seed yield due to drought stress; DSI, drought susceptibility index

[b] LSD, Least significant difference at $P \le 0.05$

maturing genotypes similar to Othello, tended to have DSI values higher or equal to 1.0. The lowest average harvest index was observed in the DS environment in 2003 (Table 2). Othello and Common Red Mexican showed the lowest reduction in the harvest index in 2003 as a result of severe drought stress. The largest harvest index reduction was observed in Common Pinto and UI 259 in the DS environment in 2003.

In 2003, WUE values were higher in the NS environment than in the DS environment for all genotypes except Othello (Table 2). The mild drought stress and generally milder and more favorable climatic conditions in 2004 (Table 1) increased the WUE values of all genotypes in both the NS and DS environments. Moreover, on average, WUE values were higher in the DS environment than in the NS environment in 2004. Thus, only under severe drought stress in 2003 was there a positive relationship between drought resistance (i.e., high seed yields in both the DS and NS combined with low percentage reduction in yield in the DS environment and a DSI value <1.0) and WUE. For example, drought-resistant genotypes such as Common Red Mexican, Othello, and NW 63 had a lower water use than the three susceptible genotypes, namely Common Pinto, UI 320, and UI 259. This clearly shows that in order for drought-resistant dry bean genotypes with higher WUE to be identified, germplasm evaluation must be carried out under conditions of a severe water deficit. Furthermore, the summer rainfall in southern Idaho (and other western states) is approximately one-tenth of the water required for normal growth and the development of the dry bean crop in the region. Thus, by scheduling the timing, frequency, and amount of water supplied through an irrigation system, it should be possible to maximize the usage of water by the drought-resistant landraces and cultivars identified in this study and to manipulate the severity of drought stress for further germplasm screening, breeding, genetics, and physiology studies.

The WUE values reported by Doorenbos and Kassam (1979) and Mahlooji et al. (2000) ranged from 3 to 6 kg $ha^{-1}$ $mm^{-1}$. Thus, in our study, only the most drought-resistant genotypes, such as Common Red Mexican and Othello, maintained WUE values within the common range reported for dry bean by these researchers, and drought-susceptible genotypes had WUE values below this range in the DS environment in 2003. In the semiarid Northern Great Plains of the USA, 'Black Turtle Soup' dry bean was found to have a mean WUE of 5.1 kg $ha^{-1}$ $mm^{-1}$ (Anderson et al. 2003). Similarly, Miller et al. (2002) reported a mean WUE of 2.9, with a range between 0.3 and 6.7 kg $ha^{-1}$ $mm^{-1}$, for dry bean across locations and years in the Northern Great Plains. The WUE is known to vary with the plant growth stage affected by drought stress. In dry bean, the lowest WUE was reported when drought occurred during flowering and pod formation stages (Calvache et al. 1997; Libardi et al. 1999; Pimentel et al. 1999). Moreover, the level of water stress can affect WUE. For example, pinto bean irrigated after 50 mm of evaporation from a class A pan had a WUE of 5.6 kg $ha^{-1}$ $mm^{-1}$, while after 90 mm of evaporation, it had a WUE of 3.2 kg $ha^{-1}$ $mm^{-1}$ (Mahlooji et al. 2000). This may suggest that the WUE values reported by Doorenbos and Kassam (1979) and Mahlooji et al. (2000) were obtained under more favorable environments than those reported in this study in the severe DS environment in 2003 and those reported by Miller et al. (2002). The WUE values observed in both the NS and DS environments in 2004 (average: 8.7 in NS and 10.0 kg $ha^{-1}$ $mm^{-1}$ in DS; Table 2) are much higher than those reported in literature. The reason for this may be the favorable climatic conditions (moderate temperature and solar radiation) that occurred in 2004: these conditions allowed all genotypes to reach a relatively higher seed yield in both the NS and DS environments despite the fact that even in the DS environment the ET ranged only between 240 and 300 mm (Table 2). These observed water use values in the present study were lower than those reported by Allen et al. (2000) and Doorenbos and Kassam (1979) for dry bean, which ranged between 300 and 550 mm for reaching high yields. Our results may further indicate that all six genotypes were well-adapted to the semiarid conditions of southern Idaho when climatic parameters such as temperature and solar radiation did not exceed the upper limits for the race Durango cultivars.

The cultivation of highly drought-resistant dry bean such as Common Red Mexican and Othello should be promoted in areas having endemic drought and recurring water shortage because they exhibited high WUE under severe drought in 2003. Under drought environments early-maturing drought-resistant cultivars such as Othello should help conserve higher amounts of water because they may be grown with fewer irrigations compared with the later maturing full-season Common Red Mexican. Furthermore, early-maturing cultivars may provide a certain flexibility for later planting or earlier harvesting, thus avoiding unexpected frost in late spring and early fall. Nonetheless, further studies may need to be conducted to determine the best irrigation schedules and amounts of water to be applied to each drought-resistant genotype. Similarly, in addition to using drought-resistant cultivars, agronomic practices that enhance soil moisture conservation and water use efficiency would be pivotal in reducing water dependency and for low-input sustainable production systems in the western USA and other regions of the world facing water shortage.

## Conclusion

Even under the most severe drought-stressed environment dry bean landraces and cultivars, irrespective of their levels of drought resistance, used mostly water available within the top 0.5m soil depth. Nonetheless, significant ($P$ = 0.05) differences for water use efficiency were found among dry bean landraces and cultivars. Under severe drought stress water use efficiency of dry bean landraces and cultivars was reduced compared with more favorable climatic conditions. Furthermore, in pinto market class, Common Pinto landrace had lower water use efficiency under drought-stress compared with cultivar Othello. In contrast, in red market class, there was a gradual reduction in water use efficiency from the landrace to modern cultivars developed subsequently. Dry bean landraces and cultivars with high water use efficiency should be used to reduce dependence on irrigation water and develop drought resistant cultivars.

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